Time Domain Reflection Technique for Microwave Non Destructive Testing of Steel Fiber Reinforced Concrete

G. Roqueta, J. Romeu, L. Jofre
AntennaLab. Department of Signal Theory and Communications. Universitat Politècnica de Catalunya
Spain
gemma.roqueta@tsc.upc.edu

***Abstract*—Preliminary results of a time domain reflection approach for the non-destructive testing of Steel Fiber Reinforced Concrete (SFRC) are presented in this paper. An open-ended epoxy-filled waveguide and a reflector plate located behind the material sample are used to measure its effective permittivity. An electromagnetic model based on the Maxwell-Garnett approach for dielectric mixtures is used to relate the effective permittivity of SFRC to its fiber dosage. Agreement with the expected dosage figures is obtained. Time domain results are compared with frequency domain results obtained in previous experiments. Conclusions regarding the suitability of this method are derived.**

I. Introduction

Steel Fiber Reinforced Concrete (SFRC) is a new material used in construction [1] made with Portland cement, aggregates and discrete steel fibers. Because of the inherent material properties of SFRC, the presence of randomly oriented and distributed fibers in the body of the concrete or the provision of a tensile skin of fiber concrete can be expected to improve the resistance of conventionally reinforced structural elements to cracking, deflection and other conditions. Microwave imaging has been proved to be an effective non-destructive technique to visualize civil engineering materials and structures [2]. For the particular case of SFRC, the interest is focused on the measurement of the density of fibers inside the material. Measurements using an open-ended coaxial probe reflectometry were reported in [3], showing promising results for the sensitivity to the fiber content in concrete. Next, a work by the authors [4] relied on the use of microwaves (300 MHz - 600 MHz) to perform a propagative frequency domain analysis of the fiber content of SFRC structures using two dielectric epoxy-filled open-ended waveguide antennas arranged in a transmission approach. From the experimental point of view the transmission geometry was chosen for its calibration simplicity and signal discrimination robustness, but from the application point of view, a reflection geometry may be more appropriate in real field, where accessibility is reduced. In this paper, preliminary results of a reflection approach based on a microwave short-range time domain analysis are presented. Time domain is chosen for its eventual simpler equipment and for better understanding of the reflection phenomena.

II. Electromagnetic Modeling of SFRC

In classical electromagnetic theory, metallic fibers can be considered as wire scatterers inside a host medium, each one inducing a dipole moment $\vec{p}$ accounting for the additional polarization density into the host. This dipole moment is defined as the volume integral of the charge density distribution on the wire ρ, excited by an incident field $\vec{E}_{in}$

$$\vec{p} = \int_V \rho(\vec{r})\vec{r}\delta V \tag{1}$$

where V is the volume of the wire and $\vec{r}$ is the position vector with respect to the relative center of coordinates of the wire. The dipole moment of a fiber is related to the incident field by

$$\vec{p} = \overline{\overline{\alpha_i}}\vec{E}_{in}, \tag{2}$$

with $\overline{\overline{\alpha_i}}$ the polarizability dyadic of the fiber. Once $\vec{p}$ is known, this polarizability may be obtained from (2). To calculate $\vec{p}$, the charge density on the wire surface is obtained using the Numerical Electromagnetic Code (NEC) [5] based on the Method of Moments (MoM). Further details on the analytical expressions of $\overline{\overline{\alpha_i}}$ may be found in [6].

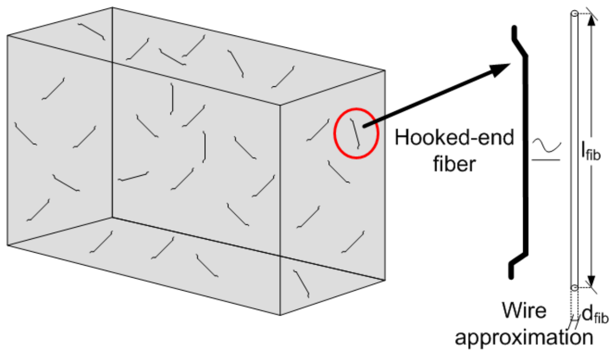

Fig. 1. Randomly oriented metal wire distribution with a zoom on a wire with $l_{fib} >> d_{fib}$.

Let us consider Fig. 1, a distribution of arbitrarily oriented thin metal wires (length l_{fib} and diameter d_{fib}). Under the low frequency approach (electrically small wires), the mixture of the wires and the host is considered to be homogeneous and the concept of effective or macroscopic permittivity of

TABLE I
EFFECTIVE PERMITTIVITY OF SFRC SAMPLES

Fiber Dosage (kg/m^3)	ϵ_{r_eff}
0	7.4 - j2.5
15	10.0 - j3.8
45	15.0 - j8.0
60	20.0 - j10.0

the SFRC composite can be used. Under these circumstances, the Maxwell - Garnett mixing rule [7] is used to model the wire scatterers inside the hosting medium. According to this rule, the Clausius - Mossotti formulation

$$\frac{\epsilon_{r\_eff} - \epsilon_{r\_h}}{\epsilon_{r\_eff} + 2\epsilon_{r\_h}} = \frac{n\alpha_i}{3\epsilon_{r\_h}\epsilon_0} \tag{3}$$

may be used to relate the relative effective permittivity of a composite (ϵ_{r_eff}) to the polarizability of the individual randomly placed wires (α_i), the relative permittivity of the host medium (ϵ_{r_h}= $\epsilon_{r\_eff,0kg/m^3}$) and the number of wires per unit volume (n).

Equation (3) was used in transmission frequency domain (300-600 MHz) measurements on SFRC samples in [4] and [8] to determine the fiber density of the composite based on the previous knowledge of the permittivity of the host medium. Results are summarized in Table I. The high values for the complex effective permittivity indicate the lossy nature of the medium.

III. TIME DOMAIN REFLECTION SYSTEM

Time domain has been chosen for reflection measurements since it allows easier understanding of the reflections in the system and may eventually allow a simpler equipment. The selection of the time domain pulse width is required to ensure that the system is capable to distinguish between the transmitted pulse and the received pulse propagated a distance $2d_m$ through the SFRC material after reflection into a metallic conductor. Under this consideration, the required pulse width for a pulse that propagates through a material with effective permittivity ϵ_{r_eff} and thickness d_m is

$$\Delta t_{tx} = \frac{2d_m}{c}\epsilon'_{r\_eff}k_\sigma \tag{4}$$

where c is the speed of light in free space. The factor k_σ is introduced as a safety margin accounting for the eventual pulse dispersion specially in high fiber dosages. This factor has been calculated looking at pulse widening of a propagated artificial Gaussian pulse defined using the paraxial approximation for Gaussian beams, such that the transmitted pulse and reflected pulse after propagating a distance $2d_m$ are distinguishable at least at the level of -10dB. Then, for measurements on a SFRC composite of thickness d_m=15cm and effective permittivity $\epsilon_{r\_eff} = 7.4 - j2.5$ (the most restrictive case), the dispersion factor is k_σ =0.7 and, according to equation (4), the pulse width generated by the system should not exceed Δt_{tx}=2ns.

As it was investigated in [4], in order to avoid self resonances of the fibers, measurements should be done below $f_{max} = \frac{2}{3}f^{1st}_{res}$, where f^{1st}_{res} is the first resonant frequency of the fibers inside the host medium and is related to half the fiber length. For the case of the standard fibers used in SFRC composites (l_{fib}=35mm) the maximum allowable frequency would be f_{max}=1GHz. In the case of considering all the spectrum such that the bandwidth is Bw=1GHz the time domain pulse width would be 1ns, which fixes the lower bound for the pulse width generated by the system.

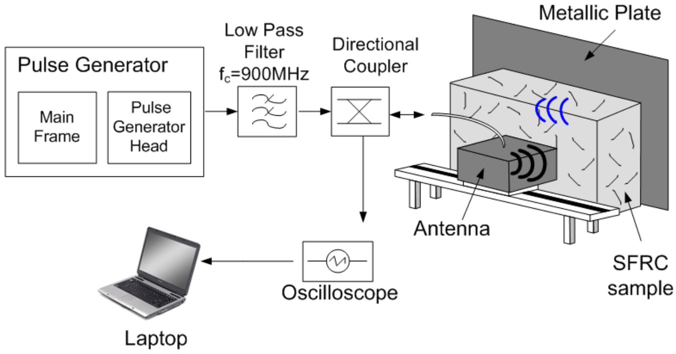

Fig. 2. Diagram of the time domain system.

Figure 2 shows the diagram of the time domain system used in this experience. A pulse generator GZ1117DN is used to generate a pulse that is sent to a SFRC structure, reflected back by a metallic reflector placed behind the structure and finally captured by an oscilloscope. A low-pas Gaussian filter with a cut-off frequency at 900MHz is used to ensure that the self resonances of the fibers are avoided. A directional coupler is used to take a sample from the transmitted and the reflected pulses separately. The applicator is an open-ended waveguide antenna whose dimensions ($\lambda \times \lambda/2$ at 400 MHz) approximately determine the pixel resolution size. At the output of the chain, pulses generated by the system have a duration of 1.2ns, which is compliant with the limits 1ns≤ Δt_{tx} ≤2ns established by the requirements of the system.

IV. COMPLEX EFFECTIVE PERMITTIVITY CALCULATION

The characterization of the relative effective permittivity of the SFRC material is required to determine the number of fibers per unit volume (n) of the composite material, applying (3). In order to obtain an estimation of the relative effective permittivity of the SFRC material, time domain results are transformed into the frequency domain to extract the values for the attenuation $\alpha(\omega)$ [Nep/m] and phase $\beta(\omega)$ [rad/m] constants. These two parameters are used in the definition of the propagation constant $\gamma(\omega) = \alpha(\omega) + j\beta(\omega)$, which characterizes the transfer function through the material. This transfer function may be obtained from the relationship between the Fourier transform of both the incident pulse $p_{tx}(t)$ and the reflected pulse $p_{rx\_i}(t)$ as

$$H(\omega) = \frac{P_{rx\_i}(\omega)}{P_{tx}(\omega)} = e^{-j2\gamma(\omega)d_m} \tag{5}$$

The attenuation and the phase constants are related to the effective permittivity of the SFRC material through [9]:

$$\begin{aligned}\epsilon'_{r\_eff}(\omega) &= \frac{\beta(\omega)^2-\alpha(\omega)^2}{\omega^2\mu_0\epsilon_0} \\ \epsilon''_{r\_eff}(\omega) &= \frac{2\beta(\omega)\alpha(\omega)}{\omega^2\mu_0\epsilon_0}\end{aligned} \tag{6}$$

where μ_0 and ϵ_0 are the free space permeability and permittivity respectively.

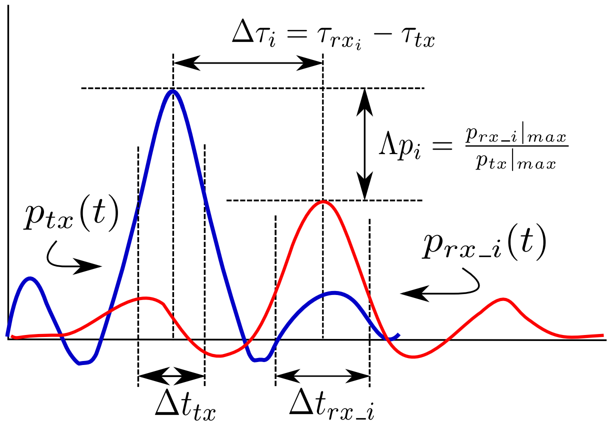

Fig. 3. Definition of the time delay ($\Delta\tau_i$) and attenuation (Λp_i) of the measured pulse ($p_{rx\_i}(t)$) propagated through the SFRC composite and reflected back to the receiver, with respect to the transmitted pulse ($p_{tx}(t)$).

Once the exact values for ϵ'_{r_eff} and ϵ''_{r_eff} have been obtained through the time-frequency conversion, we are interested in investigating the accuracy of using a direct time domain method based on a moderate loss approach ($\epsilon''_{r\_eff} < \epsilon'_{r\_eff}$). Under this consideration, the effective permittivity may be directly obtained from the measured delay $\Delta\tau_i$ and attenuation Λp_i of the received pulse defined with respect to the transmitted pulse delay and attenuation, as shown in Figure 3. According to this, the real and imaginary parts of the effective permittivity may be expressed as

$$\begin{aligned}\epsilon'_{r\_eff} &\approx \left(\frac{\Delta\tau_i c}{2d_m}\right)^2 \\ \epsilon''_{r\_eff} &\approx -\frac{\ln(\Lambda p_i)\Delta\tau_i c^2}{2\omega d_m^2}\end{aligned} \tag{7}$$

This approach may be useful to obtain an initial estimation of the effective permittivity required to calculate the fiber dosage of the SFRC composite.

V. Measurements

A set of SFRC blocks with different fiber densities (0, 15, 45 and 60kg/m^3) are used to test the time domain reflection technique proposed in this paper. Each block has a volume of 15×15×15cm^3. Fibers are steel hooked-end DRAMIX ® ZP 35/.50 type with length l_{fib}=35mm, diameter d_{fib}=0.5mm and density 7850kg/m^3. Six blocks of equal fiber dosage have been arranged forming 3×2 homogeneous structures. Thus, the inspected surface is big enough to concentrate all the incident field in its inner structure. A picture of this setup is shown in Figure 4. In this initial setup measurements are done with and without metallic plate behind the SFRC structure in order to extract the effects of multiple reflections in the system. Then, a net pulse can be obtained from the subtraction of these two measurements and the impulse response may be directly related to the propagation phenomena inside the material.

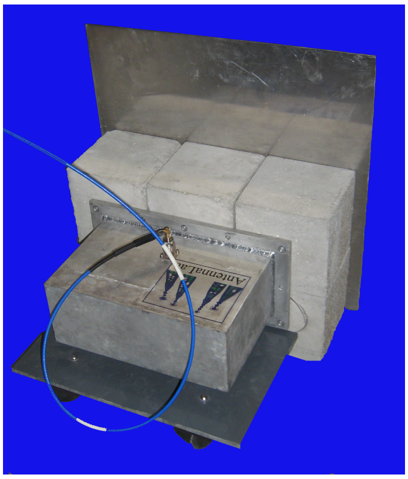

Fig. 4. Picture of the measurement setup: waveguide transceiver and 3×2 SFRC blocks structure

The reflected net pulses for the different fiber densities ($p_{rx\_i}(t)$) are shown in Figure 5. The curves are normalized with respect to the incident net pulse ($p_{tx}(t)$). The zero-time reference is associated to the incident net pulse. The increasing number of fibers generates an increment of complex permittivity which leads to a progressive increment of the attenuation and to a reduction of the velocity of propagation, so the received pulse is delayed and attenuated.

The complex effective permittivity of each specified dosage has been calculated in the transformed frequency domain according to (6). Once the exact values for the permittivity are calculated, the moderate-loss approach of (7) is used to calculate an initial estimation of the permittivity. Figure 6 collects the frequency-averaged results of the exact calculation of the permittivity, on one hand, and its initial estimation using the moderate-loss approach, on the other hand. From this figure it can be deduced that the moderate-loss time domain approach may be good estimation of the effective permittivity specially for low fiber dosages.

An estimation of the polarizability for an individual fiber (l_{fib}=35mm, d_{fib}=0.5mm) inside the host medium has been calculated using NEC (freq≤900MHz, size of the box: 30x30x30cm^3) giving a frequency-averaged value of α_i=8.6·10^{-17}Cm^2/V. Results of the frequency-averaged relative effective permittivity obtained by (6), permittivity of the host medium (ϵ_{r_h}) and polarizability (α_i) are used to calculate the fiber factor $n\alpha_i$ applying the Clausius - Mossotti equation of (3). Then, the factor $n\alpha_i$ for each kind of block has been inverted to obtain an estimation of the fiber dosage inside the SFRC blocks. Table II collects the measured frequency-averaged permittivities, the fiber factor $n\alpha_i$ and finally the

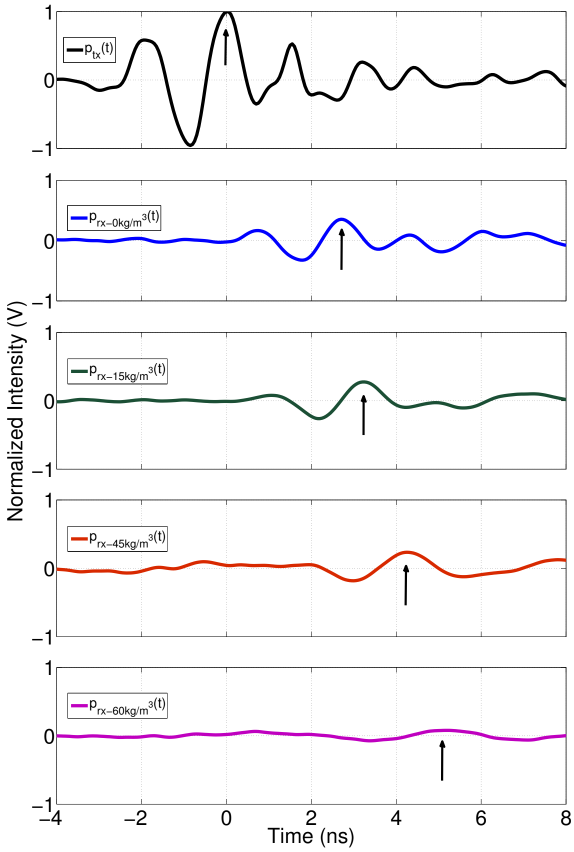

Fig. 5. Normalized transmitted net pulse and received net pulses reflected from each SFRC structure with specific fiber density (by order: 0, 15, 45 and 60kg/m^3)

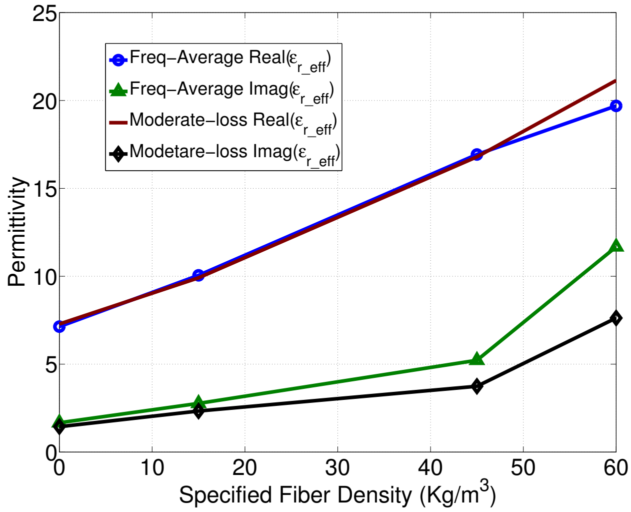

Fig. 6. Frequency-averaged complex effective permittivity $\epsilon_{r\_eff} = \epsilon'_{r\_eff}(-\!\bigcirc\!-) - j\epsilon''_{r\_eff}(-\!\triangle\!-)$ and moderate loss approximation of $\epsilon_{r\_eff} \approx \epsilon'_{r\_eff}(-) - j\epsilon''_{r\_eff}(-\!\diamond\!-)$ for each specified fiber dosage $\{$0kg/m^3, 15kg/m^3, 45kg/m^3 and 60kg/m$^3\}$.

resulting estimation of the fiber density inside the SFRC blocks. These results highlight that, for the exact calculation of the permittivity, the system is able to give an accurate estimation of the fiber dosage of SFRC blocks with a root mean square error smaller than 5%. Results are consistent in absolute values and relative rms with the results of the frequency domain transmission approach presented in [4]. The same process is used to estimate the fiber dosage from the moderate-loss model for the effective permittivity. The rms error introduced in this case increases to 8% due to the elevated losses in SFRC composites with high concentrations of fibers.

TABLE II
SUMMARY OF MEAN VALUES FOR DIFFERENT DOSAGE BLOCKS CHARACTERIZATION

Dosage	ϵ_{r_eff}	$n\alpha_i$[C/Vm]	Dosage Est.
0 kg/m^3	7.1-j1.6	0.0	0.0 kg/m^3
15 kg/m^3	10.0-j2.7	$2.2\cdot10^{-11}$	16.4 kg/m^3
45 kg/m^3	16.9-j5.2	$6.1\cdot10^{-11}$	42.6 kg/m^3
60 kg/m^3	19.6-j11.6	$8.6\cdot10^{-11}$	57.0 kg/m^3

VI. CONCLUSIONS

A time domain reflection approach for the non-destructive characterization of Steel Fiber Reinforced Concrete (SFRC) has been presented in this paper. The Maxwell Garnett approach for dielectric mixtures has been used to relate the effective permittivity of a SFRC block to its fiber dosage. Several SFRC testing blocks of different fiber dosages have been analyzed in this experiment. An open-ended epoxy-filled waveguide in a reflection mode has been used to measure the effective permittivity of each sample. A frequency-averaged value for the effective permittivity of each sample has been calculated from the time-frequency converted data. This value has been finally used in the inversion problem of the Clausius-Mossotti equation to estimate the fiber dosage of the blocks with a rms error smaller than 5%. The time domain reflection approach presented herein has proven to be consistent in absolute values and relative rms error with the transmission frequency domain approach developed in previous experiences, with the advantage of allowing simpler instrumentation and being more appropriate for practical situations in real environments.

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